EXPLOSIVE MAGNETIC LINER DEVICES TO PRODUCE SHOCK PRESSURES UP TO 3 TPa*

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Abstract

The paper discusses devices with a Disk Explosive Magnetic flux compression Generator (DEMG), which are similar to the ALT-1,2 experimental devices and are intended for testing the possibility of producing 1-3 TPa (10-30 Mbar) pressures and the possibility of measuring Hugoniots of different materials at such pressures. It is expected that two-layer, cylindrical liners, Al+Fe and/or Al+W, will be used, driven by 4-5 MG magnetic fields to ~ 20 km/s velocities.

The paper presents and discusses simulated characteristics of these devices, in which currents, energies and powers delivered to the liner load can reach ~ 70 MA, ~ 40 MJ and ~ 20 TW and exceed those in the ALT-1,2 devices by a factor of ~2, ~ 4 and ~ 7, respectively.

I. INTRODUCTION

Electromagnetic implosion of cylindrical condensed liners (azimuthal magnetic field B_φ) is of great interest for high energy density physics, in particular, for the generation of terapascal pressures and measurements of Hugoniots of materials at such pressures, see e.g. [1-7]. Pulsed power systems based on Disc Explosive Magnetic flux compression Generators (DEMG) deliver particularly high currents to the liner load. The use of an electrically exploded foil opening switch (FOS) in such systems reduces the effective rise time of current in the liners down to 1-2 μs, which allows accelerating liners with a mass of 50 g (~13g/cm) and more to ~20 km/s or higher velocities [3,7]. We consider cylindrical Al liners and two-layer liners, whose current carrying Al layers interface with internal layers of higher-density materials (Fe, Mo, W, …), which at such velocities are capable of producing shock pressures up to 1-3 TPa in different materials [1,3,7].

The first experiments in this area, ALT-1,2 (Advanced Liner Technology, 1999-2000) with a ten-module 0.4 meter diameter DEMG demonstrated stable operation of this device (see Fig. 1) and were in good agreement with pre-shot simulations. In ALT-1, with a peak current of J_{max} = 31.5 ± 1.5 MA in the ponderomotive unit (PU), a cylindrical Al liner of 4 cm height, 4 cm radius and 0.2 cm thickness (~50 g mass) impacted a 2 cm diameter central measuring unit (CMU) at a velocity of $v_{imp} \approx 12$ km/s.

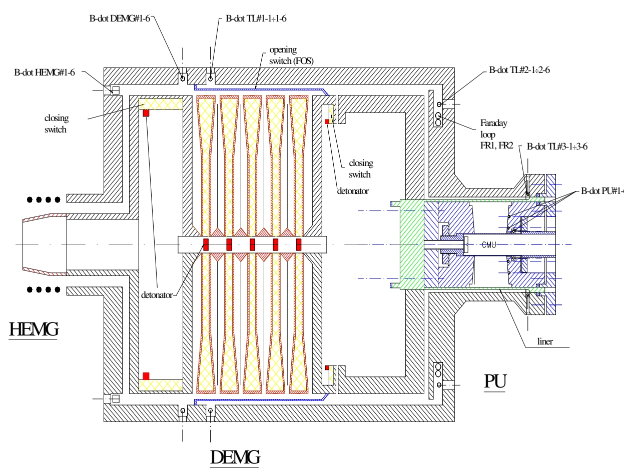

Figure 1. Schematic drawing of explosive magnetic liner device and its diagnostics in ALT-1,2 experiments [2].

Ref. [6] presents refined (compared to [5]) 2D magnetohydrodynamic (MHD) simulations of Rayleigh-Taylor instability development for this liner, showing small time differences of liner impact on the CMU (20 - 30 ns), which agree with experimental data [2]. Refs. [4] and [7] consider devices similar to [2, 3], with 7- and 15-module 0.4 meter diameter DEMGs that can provide up to

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14. ABSTRACT **The paper discusses devices with a Disk Explosive Magnetic flux compression Generator (DEMG), which are similar to the ALT-1,2 experimental devices and are intended for testing the possibility of producing 1-3 TPa (10-30 Mbar) pressures and the possibility of measuring Hugoniots of different materials at such pressures. It is expected that two-layer, cylindrical liners, Al+Fe and/or Al+W, will be used, driven by 4-5 MG magnetic fields to ~ 20 km/s velocities. The paper presents and discusses simulated characteristics of these devices, in which currents, energies and powers delivered to the liner load can reach ~ 70 MA, ~ 40 MJ and ~ 20 TW and exceed those in the ALT-1,2 devices by a factor of ~2, ~ 4 and ~ 7, respectively.**			
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~ 40 and ~ 60 MA currents in the same PU and ~ 15 and ~ 22 km/s velocities of the same liner, respectively.

The devices of Refs. [2-4, 7] were simulated using the $1D(MHD)_n$ code (see e.g. [9]) developed on the basis of the UP-OK technique [8] and intended for "end-to-end" simulations of electrophysical devices with different power supplies, opening and closing switches, transmission lines and loads (PU). In this code, all major units of these devices are simulated taking into account their geometry and materials by joint processing of an arbitrary number (n) of separate 1D MHD problems coupled by means of boundary and other conditions. 13-year practice of using this code shows that currents in the devices can be predicted with accuracy, which is close to that of current measurements by B_{dot} probes (±5%).

This study considers more efficient (compared to [2-4, 7]) similar devices being developed at VNIIEF. Their simulated performance data obtained using the $1D(MHD)_n$ code are presented. In particular, with the expected PU currents of up to ~ 70 MA, two-layer Al+W and Al+Fe cylindrical liners with a mass of ~75 g (~20 g/cm) can be accelerated by 4-5 MG magnetic fields, and their velocities on impact with the 2 cm diameter CMU can reach the required level of $v_{imp} \approx 20$ km/s. The efficiency of liner implosion, however, will depend on the ability to restrain their instability and on the synchronism of their impact on the CMU. We are going to study this using 2D MHD simulations similar to [6]. The above instability is the central problem in liner implosion: it propagates from the outer liner surface and may lead to a complete failure of the liner.

II. PHYSICAL CONFIGURATIONS OF THE DEVICES

Two devices with a 15-module 0.4 m diameter DEMG are being developed, in which one explosive that has been used before (HE_{old}) is replaced with a different one, which is technologically more efficient (HE_{new}) and has an insignificant effect on the simulated performance of the devices [7]. One of the devices, as distinct from the ALT-1,2 experiments [2] and study [3], has no explosive closing switch (ECS) in the load, - like in the devices of Refs. [4,7], see Figs. 2 a, b. The other uses this ECS: It cannot be ruled out that the instability of liner implosion will prove to be less destructive due to the short total rise time (2-3 microseconds) in this device. Both devices use a new 0.4 meter diameter helical EMG to deliver 6.5±0.5 MA initial current to the DEMG (HEMG, see Figure 2b).

The high (compared to [3]) efficiency of both devices is basically associated with three factors: increased thickness of the Cu foil in the FOS (0.12 → 0.18 mm), low load inductance (~ 4 nH, which is a factor of ~ 2 smaller than in the ALT-1,2 devices) and small losses in the PU due to a smaller PU height ($H_{pu} \approx 15 \rightarrow 6$ cm) and replacement of the thin reverse Al current carrier over the liner with a thick Cu one, cf. Figs. 2b and 2a.

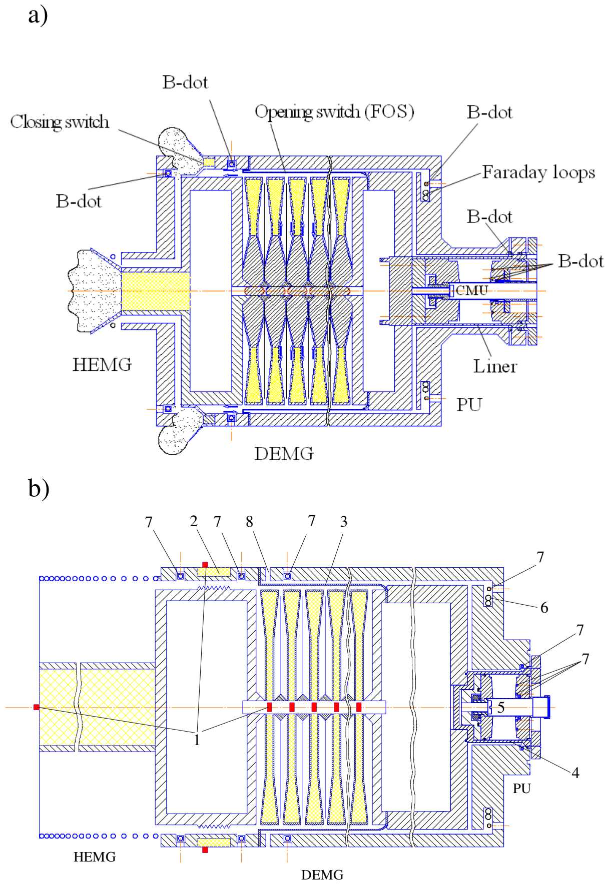

Figure 2. Schematic drawing of the device without ECS from Ref. [7] (a) and proposed devices without ECS and with ECS (b).
1 – detonators; 2 – ECS to disconnect HEMG from DEMG; 3 – FOS; 4 – liner; 5 – CMU; 6 and 7 – Faraday loops and B-dots; 8 – place to install ECS to connect PU to FOS (if necessary).

As distinct from the ALT-1,2 devices, two-layer liners, 2 mm Al and 0.3 mm Fe or 0.12 mm W, are used, - without changing their radius and effective height (~ 40 mm). The shape of the PU glide planes will be chosen based on the outcome of 2D MHD liner implosion simulations similar to those discussed in Ref. [6]. The device, which will be expected to have higher impactor implosion efficiency, will be chosen for experiments.

As distinct from the ALT-1,2 experiments, diagnostic capabilities of the CMU for liner efficiency assessment will be enhanced [7]: in addition to VISAR (measurements of inner liner surface velocity) and light shock sensors (measurements of synchronism of liner impact on the 2 cm diameter CMU Fe housing), a PDV system will be used [11]. We are going to test the

possibility of measuring Hugoniots of materials, ~20 samples of which (Al, Fe, Mo, W,…) can be placed on the CMU housing. These samples, the CMU housing and the liner are expected to be fabricated with high precision [1,3, 7].

III. SIMULATION RESULTS AND THEIR DISCUSSION

Table 1 gives the basic characteristics of devices 1-5 from Refs. [1, 7] ($H_{pu} \approx$ 15 cm (Al), see Figs. 1 and 2a) and devices 6-15 ($H_{pu} \approx$ 6 cm(Cu), see Fig. 2b) considered in this study.

Results of simulation 1 of the experimental device with ECS are close to the ALT-1 experiment, see Introduction. In the similar devices with 15- and 7-module DEMGs (HE_{old}) with ECS, the PU current can be increased to ~ 46 MA, and velocities of the same liner may grow to ~ 18 and ~ 16 km/s, see simulations 2 and 6. In the proposed device with a 15-module DEMG (HE_{new}) with ECS, the PU currents are expected to reach ~ 72 MA, and velocities of the same Al liner may grow to ~ 27 km/s, see simulation 12. Note that according to the 1D MHD simulations, ~ 20% of liner mass will remain solid (in ALT-1,2, ~ 40%).

A similar device without ECS considered earlier [7] might provide PU currents up to ~ 61 MA and accelerate the same liner to ~ 22 km/s (simulation 3). Computational performance optimization of the devices was conducted taking into account the parameters chosen for the same device with a 7-module DEMG (HE_{old}, simulation 5). The 7-module system is capable of producing up to ~ 49 MA PU currents and accelerating the same liner to ~ 17 km/s (simulation 7). The proposed device with a 15-module DEMG (HE_{new}) without ECS may provide higher currents and velocities of the same Al liner, ~ 67 MA and ~ 23 km/s (simulation 8).

The two-layer liners in the proposed devices without ECS (9-11) and with ECS (13-15) may attain up to 21-22 km/s velocities. Simulated profiles of MHD quantities in the Al+W liner before its impact on the CMU show (see Figs. 3 a,b) that in the devices with ECS and without it, the W impactor and ~ 17 and ~ 27% of the adjacent Al current carrier mass, respectively, remain solid (the device without ECS in this respect is preferable).

Table 1. Performance of liner devices with ECS (1, 2, 6, 12-15) and without ECS (3-5, 7-11, bold face) – with different explosives in the DEMG: HE_{old}(1, 2, 4-7) and HE_{new} (3, 8-15, italics).

#	N	I_0 MA	Δ_f mm	H_f cm	L_{0l} nH	$\Delta_{Al}+\Delta_Z$ mm
1[2]	10	6	0.12	72	7.5	2
2[7]	15	7	0.16	108	8	2
3[7]	***15***	***7***	***0.18***	***108***	***4***	***2***
4[7]	**15**	**7**	**0.18**	**108**	**4**	**1.5+0.11W**
5[7]	**7**	**7**	**0.18**	**72**	**3.5**	**2**
6	7	7	0.18	50	3.5	2
7	7	7	**0.18**	**50**	**3.5**	**2**
8	***15***	***7***	***0.18***	***108***	***4***	***2***
9	***15***	***7***	***0.18***	***108***	***4***	***2+0.3Fe***
10	***15***	***6***	***0.18***	***108***	***4***	***2+0.12W***
11	***15***	***7***	***0.18***	***108***	***4***	***2+0.12W***
12	*15*	*7*	*0.18*	*108*	*4*	*2*
13	*15*	*7*	*0.18*	*108*	*4*	*2+0.3Fe*
14	*15*	*6*	*0.18*	*108*	*4*	*2+0.12W*
15	*15*	*7*	*0.18*	*108*	*4*	*2+0.12W*

Table 1 continued (simulation results)

#	U_{fm} kV	I_{gm} MA	I_{lm} MA	v_{imp} km/s	t_{imp} μs
1[2]	205	35.4	31.3	12.0	30.4
2[7]	314	56.6	45.7	17.9	29.2
3[7]	***380***	***96***	***61.0***	***21.6***	***27.9***
4[7]	**375**	**96**	**61.6**	**19.4**	**28.2**
5[7]	**185**	**74**	**43**	**15.0**	**29.9**
6	144	64.1	46.4	16.2	29.9
7	**173**	**75.8**	**48.8**	**17.4**	**29.5**
8	***362***	***96.5***	***66.6***	***23.4***	***27.5***
9	***325***	***98.9***	***73.5***	***21.4***	***28.0***
10	***279***	***97.0***	***69.5***	***19.5***	***28.5***
11	***329***	***98.6***	***72.6***	***21.1***	***27.9***
12	*255*	*89.9*	*71.6*	*27.1*	*27,9*
13	*249*	*90.9*	*75.4*	*22.2*	*28,3*
14	*246*	*85.0*	*68.8*	*19.2*	*28,9*
15	*249*	*90.9*	*74.3*	*21.9*	*28,3*

Designations in Table 1: N and I_0 – number of modules and initial current in DEMG, Δ_f and H_f – thickness and height of Cu foil in FOS, L_{0l} – initial inductance of load from the FOS foil to the PU liner, Δ_Z – liner thickness and material; U_{fm} – peak voltage on the FOS Cu foil, I_{gm} and I_{lm} – peak currents in DEMG and PU, v_{imp} and t_{imp} – velocity and time of liner impact on the 2 cm diameter CMU (from DEMG firing).

These liner regions satisfy the solid-state criterion based on the yield strength, Y > 0 [4], and the temperature lies within the following range (see Fig. 3b):

$0.12\ \text{eV} \le T < T_m \approx 0.34\ \text{eV}$.

Here, T_m is the melting point (Y=0 at $T \ge T_m$), which is considerably higher than that of aluminum under normal conditions, $T_{om} = 0.08$ eV, - due to large (a factor of ~1.5) compression of aluminum. Near the outer Al surface, magnetic fields reach ~5.5 MG, and maximum temperatures, ~17 eV, see Fig. 3a (the regions near the outer surface are cooled due to heat conductivity and radiation).

At initial DEMG currents of $I_0 = 6 \div 7$ MA, such impactors can attain the required velocities of ~20 km/s (simulations 9-11, 13-15) and, according to the 1D MHD simulations, generate shock pressures in test samples of up to ~3TPa (W-W), ~2TPa (W-Fe), ~1 TPa (W-Al, Fe-Fe). Note that here we use greater impactor thicknesses than in Refs. [7] (simulation 4 in Table 1) and in Ref.[3]. The latter considered similar devices with 15- and 25-module DEMGs (HE_{old}) with ECS, which could provide up to ~38 and ~57 MA PU currents and velocities of thinner Al+W liners (1.1 and 1.25 mm Al) up to only ~16 and ~20 km/s, respectively.

Figs. 4 a,b show basically the characteristics of Al+W liner implosion in the proposed devices without/with ECS as a function of time, see simulations 11 and 15 in Table 1. Liner currents in these devices reach peak values of ~73 and ~74 MA with a magnetic field on the outer liner surface of ~4 MG (t ≈ 26.7 µs), when the W liner layers move at a distance of ~8 and ~5 mm, respectively (characteristic accelerating magnetic fields of ~5 MG are achieved ~1 µs later).

The proposed pulsed power systems with a 15-module DEMG are rather efficient. Table 2 summarizes their basic characteristics (from simulations 11 and 15, see Figs. 4c,d and Table 1), - compared to the same data for the ALT-1 experiment, for devices with a 7-module DEMG, and for the experiment with the same 15-module DEMG, - from simulations 1 and 6-7 in Table 1 and from Ref. [10] **). One can see, in particular, that the values of W_{fm}, E_{lm} and S_{fm} in the proposed devices with a 15-module DEMG can be a factor of ~2, ~3 and ~4 higher than in the device from Ref. [10], but with lower FOS voltages: 330 and 250 kV instead of ~430 kV.

**) In the experiment of Ref. [10] (N = 15, I_o = 6.5 MA, H_f = 108 cm, Δ_f = 0.155 mm, L_{0l} = 10 nH), the Al liner (R_l = 3cm, Δ_l= 0.2 mm, H_l = 1 cm) was driven to ~50 km/s at an impact radius of ~0.8 cm, but the liner was electrically exploding, .i.e. unsuitable for the use as an effective impactor.

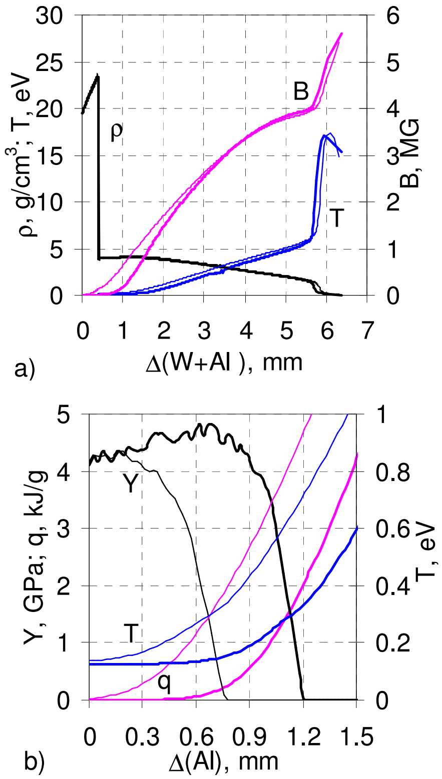

Figure 3. Simulated distributions of density ρ, magnetic field B, temperature T, Joule heating q and yield strength Y across the liner radius before liner/CMU impact in devices without ECS (heavy lines) and with ECS (11 and 15 in Table 1). $\Delta = r - r_{in}$, r_{in} is inner radii of the liner's W layer (a) or Al layer (b).

Table 2. Simulated performance of pulsed power systems with N-module 0.4 meter diameter DEMGs without ECS (bold face) and with ECS

N (# in Table 1)	10 (1) exp	7 (6)	**7 (7)**	15 (1) exp	15 (15)	**15 (11)**
E_{gm}, MJ	10	12	**15**	-	33	**41**
U_{fm}, kV	200	140	**170**	430	250	**330**
W_{fm}, TW	3	5	**7**	10	17	**21**
S_{fm}, MJ	10	13	**14**	10	39	**37**
E_{lm}, MJ	5	5	**7**	6	13	**17**
I_{lm}, MA	31	46	**49**	35	74	**73**

Designations in Table 2 (see Fig. 4 a,c,d): E_{gm} – peak magnetic energy in DEMG; U_{fm} – peak voltage on FOS; W_{fm} and S_{fm} – peak power and maximum electromagnetic energy delivered through FOS to the load; E_{lm} and I_{lm}– peak magnetic energy and current in the load.

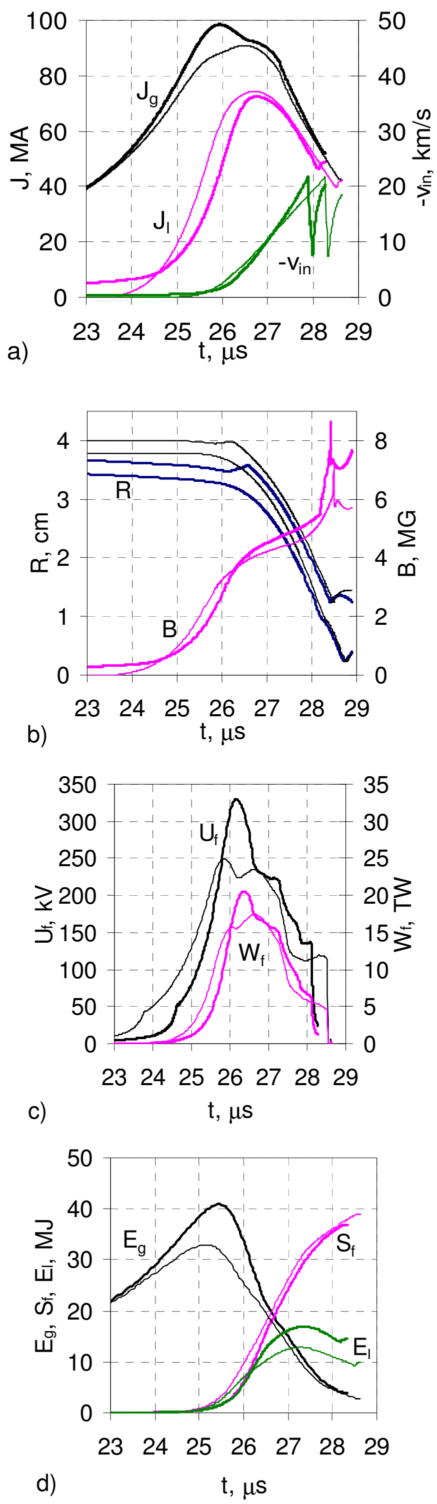

Figure 4. Simulated DEMG and load currents, I_g and I_l, velocity of inner liner surface v_{in}, radii of both liner surfaces (R_{in}, R_{out}) and magnetic field B_{out} on outer liner surfaces (a, b); FOS voltage U_f, power W_f and electromagnetic energy flux S_f delivered through FOS to the load, magnetic energies E_g and E_l in the DEMG and in the load (c, d), - in devices without ECS (heavy lines) and with ECS (11 and 15 in Table 1).

IV. CONCLUSION

The paper presents physical configurations and simulated parameters of devices intended for testing the implosion efficiency of cylindrical impacting liners and for measuring the Hugoniots of condensed materials. We consider ALT-1,2-like liner devices of the DEMG+FOS+PU type, whose simulated peak power and maximum magnetic energy transferred through the FOS to the liner load can achieve ~ 20 TW and ~ 40 MJ. These values are ~ 7 and ~ 4 times higher than those in the ALT-1,2 experiments and ~ 2 and ~ 4 times higher than in the experiment of Ref. [10], - where the same 0.4 meter diameter DEMGs were used in the 10- and 15-module configuration, respectively.

According to the simulations, devices with a 15-module 0.4 meter diameter DEMG may provide up to ~ 70 MA PU currents and up to ~ 27 km/s velocities of 4 cm radius 2 mm thick Al liners at an impact radius of 1 cm (in the ALT-1 experiment: ~ 32 MA and ~ 12 km/s). It is proposed to use two-layer liners having a radius of ~ 4 cm with a ~ 2 mm thick Al layer (current carrier) and an adjacent inner ~0.3 mm thick Fe or ~ 0.12 mm thick W layer (impactor). When driven by 4-5 MG magnetic fields, such impactors may attain velocities of ~ 20 km/s and, according to 1D MHD simulations, generate shock pressures up to 1-3 TPa in test samples (Al, Fe, Mo, W, …), which are expected to be placed in the 2 cm diameter CMU.

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